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EFFECTS OF U.S. NAVY DIVER TRAINING ON PHYSIOLOGICAL PARAMETERS, TIME OF USEFULL CONSCIOUSNESS, AND COGNITIVE PERFORMANCE DURING PERIODS OF NORMOBARIC HYPOXIA

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14. ABSTRACT
Purpose: To investigate if U.S. Navy diver training has an effect on physiological parameters (i.e., heart rate [HR] and SpO_2 levels), time of useful consciousness (TUC), and cognitive performance during periods of normobaric hypoxia. **Methods**: Each subject completed a helmet and aviator mask fitting, SynWin multitask battery training, a normobaric hypoxia symptom familiarization session, and a data collection session which consisted of simulated altitudes of 0 feet above MSL (0k), 18,000 feet (5,486 m) above MSL (18k), and 25,000 feet (7,620 m) above MSL (25k). Three separate two-way multivariate analysis of variance (MANOVA) were run for each simulated altitude with GRP (diver, non-diver) as the between-subjects variable were conducted for SpO_2, HR, TUC, and SynWin composite score (SCS) data. Bonferonni corrections were applied as necessary to maintain a family-wise alpha of 0.05. **Results**: The results of the MANOVAs indicated that USN diver training had no effect on Fg-SpO_2, HR, TUC, or SCS for the 0k, 18k, and 25k exposures. **Conclusions**: There were no significant differences between diver and non-diver physiological parameter measurements, TUC, and cognitive performance during any of the normobaric hypoxic exposures. The results of this study will help to validate the use of a 60% cut-point for SpO_2 levels as one input for a physiological based definition of TUC. Future research should focus on developing a model that incorporates a 60% SpO_2 cut-point, as well as changes in HR and blood pressure data that are based on the subject's individualized normative data.

15. SUBJECT TERMS
U.S. Navy diver, U.S. Navy aviator, hypoxia, ROBD, simulated altitude, SpO_2, heart rate, SynWin

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INTRODUCTION

Hypoxic hypoxia can result in cognitive deficits (e.g., mental confusion or poor judgment), dizziness, fatigue, shortness of breath, visual impairment (e.g., partial or complete blindness), nausea, numbness and tingling, loss of neuromuscular control (e.g., partial paralysis of a limb) as well as hypoxia-induced loss of consciousness.[1] Resistance to the detrimental effects of hypobaric hypoxia depends on the partial pressure of the oxygen (PO_2) in the inspired gas as well as individual physiological factors.

The effects of hypobaric hypoxia are often compounded with differences in oxygen concentration between the output of aircraft oxygen supply and breathing gas in the mask. These differences can be a direct result of failures of aircraft on-board oxygen systems, mask leakage, and/or carbon monoxide entering the cockpit. Traditional or legacy cockpit warnings are typically based on the PO_2 in supplied gas, rather than on physiological data, and/or performance based factors. Hypoxia recognition training is mandated for all active U.S. Navy (USN) personnel with flight qualifications. Hypoxia recognition training teaches personnel to recognize early signs of cerebral or cognitive impairment due to hypobaric hypoxia.[2,3] However, even with hypoxia recognition training there still is a need to develop a monitoring system that can detect subtle hypoxia-related changes in physiological, cognitive and psychomotor functioning and alert the user.

A hypoxia monitoring system would require a warning to provide sufficient time to perform mitigating actions prior to any loss of useful cognitive function. However, currently is no accepted definition for "time of useful consciousness" (TUC). There is a large amount of variability in an individual's susceptibility to hypobaric hypoxia that can directly affect TUC. Larger individuals have a larger reserve of dissolved oxygen in their body fluids as well as higher blood hemoglobin concentrations.[4] TUC can vary depending on altitude with accepted values of 20-30 minutes or more at 18,000 feet above mean sea level (MSL) and 3-5 minutes (180-300 seconds) at 25,000 feet MSL.[5] Research on TUC has been performed in a low pressure chamber under hypobaric conditions, focusing on exposures to simulated 25,000 feet MSL. These studies have utilized various definitions of TUC, including: the time to no longer write legibly,[6] time to make two cognitive errors,[7] and time to ineffective mask removal and reconnection.[8-10] These studies have reported TUC values ranging from 201.5 ± 8.8 s to 280 ± 73 s.[6-10]

Recent studies on TUC and hypoxia recognition training by the USN and U.S. Air Force have begun to utilize a reduced oxygen breathing device (ROBD) to simulate hypoxia under normobaric conditions.[11] The main advantage of such an approach is no danger of decompression or barotrauma when used at MSL. Research efforts have shown that hypoxia-related physiological parameter measurements, performance test results and hypoxia symptoms induced by a ROBD are similar to those induced by a low pressure chamber.[2,3,11] The ROBD is now widely used to simulated altitudes up to 25,000 feet MSL during hypoxia recognition training.[2]

The Naval Air Warfare Center – Air Craft Division (NAWCAD) has used the ROBD in a recent ongoing research effort to further define TUC, with the intent to develop a physiological and performance-based hypoxia detection system. The results of this study indicated that TUC at 25,000 feet MSL was 260 ± 145.04 s.[12-14] The TUC definition was either the time at which the subject voluntarily called to stop the hypoxia exposure (i.e., initiate 100% oxygen to the breathing supply) or when the blood nail bed oxygen saturation level (i.e., Fg-SpO2) dropped below 60%. A subject who had undergone USN Diver training demonstrated an almost three-fold greater TUC at 25,000 feet MSL when compared to subjects who had not undergone this training.[12] The present study sought to compare the results of the aforementioned NAWCAD study to additional subjects who had undergone USN Diver training. Thus, the objectives of this study were to investigate the effects of USN Diver training on physiological parameters (i.e., heart rate and Fg-SpO_2 levels), TUC, and cognitive performance during periods of normobaric hypoxia. These data will be used to further define a TUC endpoint suitable for use during military operations.

METHODS

GENERAL

This task is part of a larger effort sponsored by the Office of Naval Research Fiscal Year 2013 Force Health Protection Future Naval Capability: Hypoxia Alert and Mitigation Program, to provide a more precise definition of TUC, its kinetics and improve current hypoxia prediction and detection tools. Analyses performed in this study include data collected as part of a separate study approved by the NAWCAD Institutional Review Board, titled “Determination of Time of Useful Consciousness during Hypoxia” (DNHRPP assurance #NAWCAD.2008.0001).[12] In that study, 25 males (mean age 34 ± 8 years) and 4 females (mean age 29 ± 4 years) participated.[12]

This task was conducted in the Navy Experimental Diving Unit (NEDU) Physiological Performance Laboratory, Panama City, FL. The NEDU Institutional Review Board approved the protocol. Fifteen qualified male USN Divers from NEDU participated in this study. All divers gave written informed consent prior to participation in the study. The mean age of these divers was 33 ± 12 years and average diving experience was 12 ± 11 years.

Each subject completed a helmet and aviator mask fitting, psychomotor multitask battery training, a normobaric hypoxia symptom familiarization session, and a data collection session.

Helmet and aviator mask fitting – Subjects were properly fitted individually for a helmet and aviator mask by USN Parachute Riggers from USN Survival Training Center Pensacola, FL.

Psychomotor multitask battery training – Subjects trained on a psychomotor multitask battery, SynWin, until their performance reached an asymptote for three trials.[15]

Normobaric hypoxia symptom familiarization session – Subjects were given tables containing information pertaining to equivalent ambient PO2, percentage of oxygen (%O_2), severity scale, and types of hypoxia symptoms they may experience. These signs and symptoms have considerable individual variability; however, individuals have been shown to follow similar patterns during repeated exposures.[16] Subjects had access to the tables during the familiarization session where they were exposed to various simulated altitudes (Figure 1).

Data collection session – The data collection session occurred on a separate day from the familiarization session day (Figure 2).

EXPERIMENTAL DESIGN AND ANALYSIS

Study Design: A prospective study with independent comparisons against pre-existing data.

Variables: The independent variable was group (GRP). There were two levels for GRP, divers (i.e., active duty service members with USN diver training) and non-divers (i.e., subjects without USN diver training). The dependent variables were SynWin Composite Score (SCS), Fg-SpO_2, heart rate (HR), and TUC. TUC for this effort was defined as either the point the subject voluntarily called for 100% O_2 or the point the Fg-SpO_2 dropped below 60%.

Data collection: Signals from the pulse oximeter were integrated, digitized, and displayed graphically in real time in LabView (National Instruments) and logged at 20 Hz. Event markers in the file indicated start of data collection, each altitude transition, ending of TUC, and end of data collection. An investigator initiated and terminated logging and set the event markers. All data processing and reduction occurred prior to data analyses

Data Analysis: To evaluate the effect of USN diver training on the physiological parameters and cognitive performance during simulated altitude exposure, three separate two-way multivariate analysis of variance (ANOVA) with GRP (diver, non-diver) as the between-subjects variable were conducted for the Fg-Sp$O_{2,}$ HR, TUC, and SCS data. Separate multivariate ANOVAs were run for the following altitudes: (1) 0 feet above MSL (0k), (2) 18,000 feet (5,486 m) above MSL (18k), and (3) 25,000 feet (7,620 m) above MSL (25k). Bonferroni corrections were applied as necessary to maintain a family-wise alpha of .05.

EQUIPMENT AND INSTRUMENTATION

Reduced Oxygen Breathing Device-2: This study used a MBU-12/P oxygen mask in conjunction with a second generation Reduced Oxygen Breathing Device (ROBD-2; Series 6202, Environics®, Tolland, CT). The ROBD-2 is a commercially available off-the-shelf device that can simulate altitude and induce hypoxia under normobaric conditions. Normobaric hypoxia is generated from MSL air, normally 21% oxygen (O_2) and 78% nitrogen (N), by reducing the %O_2 and raising the %N so that the resulting gas mixture has a PO2 that approximates a target altitude. Complete technical details for the device are available from the manufacture's website.[17]

Multi-psychomotor task: SynWin was run on a PC or laptop and presents four tasks that were performed simultaneously.[15] The first task is a standard Sternberg memory task in which a string of letters is briefly displayed, followed by the appearance of a single letter, and it has to be determined if the letter was part of the previously displayed string by clicking a 'yes' or 'no' button. The second task is an arithmetic task in which two or three three-digit numbers are added using a mouse. The third task is a visual monitoring task in which a gauge with a needle ticks down from 100 to zero. The goal is to click on the gauge to "refill" it before it reaches zero. The fourth task is a vigilance task involving auditory monitoring. Subjects are presented short individual tones every 10-20 s and when they detect the higher pitch, they click a button. For the purposes of this effort the overall combined performance score (i.e., SCS) was analyzed.

Peripheral oxygenation monitoring: Fg-SpO_2 levels were measured using a pulse oximeter placed on the left index finger (ROBD-2; Series 6202, Environics®, Tolland, CT).

Heart rate monitoring: HR was measured using a pulse oximeter placed on the left index finger (ROBD-2; Series 6202, Environics®, Tolland, CT).

PROCEDURES

Psychomotor task training: Each subject was required to train in the psychomotor task battery. Training was given in a shirtsleeve environment, so no preparation, special dress or monitoring was required for these training sessions. Before beginning data collection, the subject had to become proficient in the task battery to limit learning or practice effects from confounding the results. Training sessions lasted approximately 30 min, and each subject was expected to continue training until his performance reached an asymptote (i.e., no longer show improvement from one session to the next). While the time to reach this plateau naturally varies from one individual to the next, performance typically plateaus after 3-5 training sessions.

Hypoxia Familiarization Session Procedures: Subjects reported to the NEDU Testing site fit and well rested, wearing t-shirt and gym shorts. Subjects were given information pertaining to the equivalent ambient partial pressure of oxygen (PO2) and %O_2 (Table 1).

Table 1. Altitude & equivalent ambient partial pressure of oxygen and percentage of oxygen.

Altitude (ft)	Equivalent Ambient PO2 (mmHg)	Equivalent Ambient %O2 (±0.5)
0	159.2	21%
10,000	109.5	14%
18,000	79.6	10%
25,000	59.2	7%

Note. Partial pressure of oxygen = PO2; percentage of oxygen = $\%O_2$.

Subjects were provided a subjective severity scale (Table 2) and examples of hypoxia symptoms (Table 3) they may experience. These signs and symptoms have considerable individual variability, but individuals tend to follow the same pattern during repeated exposures.[16]

Table 2. Subjective scale for hypoxia severity

Index	Verbal Descriptor
0	none
1	scant
2	noticeable
3	light
4	mild
5	somewhat
6	moderate
7	considerable
8	strong
9	severe
10	maximal

Subjects were restrained in a seat with a lap and shoulder harness and instrumented with one channel of oxygen saturation at the finger level (i.e. Fg-SpO_2). No data were collected for analytical purposes.

The ROBD-2 breathing gas mix was connected to the aviator mask inlet valve and checked for leaks. Prior to the start of simulated altitude exposure, participants breathed diver air with a normal concentration of oxygen (MSL or 21%). While performing the task battery, breathing gas was altered to achieve the simulated altitude profile (Figure 1). Subjects performed the psychomotor task battery for five minutes to warm-up prior to beginning the simulated altitude profile.

Table 3. Hypoxia signs and symptoms

Category	Symptoms
Behavioral	change in mood or personality
	apprehension
	Euphoria
Cognitive	difficulty with mathematical calculations
	impaired judgment
	impaired memory/recall
	mental confusion
	slips or lapses in aircraft operating procedures
Physical	fatigue or drowsiness
	feeling light-headed
	headache
	hot or cold flash
	increased rate and/or depth of breathing
	loss of muscle coordination
	numbness
	tachycardia
	tingling of fingers or lips
Psychomotor	difficulty with communications
	impaired manual dexterity
	slowed reaction time
Visual	impaired peripheral vision
	impaired visual acuity

After the five minute warm-up, the inspired gas mixture was altered to simulate altitude without the subject's knowledge. Subjects were told to notify the investigation team when they had experienced symptoms and rate the severity. If the symptoms progressed to the point subjects felt they could not continue, a switch was activated by a member of the research team that caused the inspired gas mixture to switch to 100% oxygen until Fg-SpO_2 levels returned to normal. At this time, the ROBD-2 automatically reset to MSL.

The simulated altitude profile (i.e., exposure) involved exposures of 0k, 10k and 25k. The profile is illustrated in Figure 1.

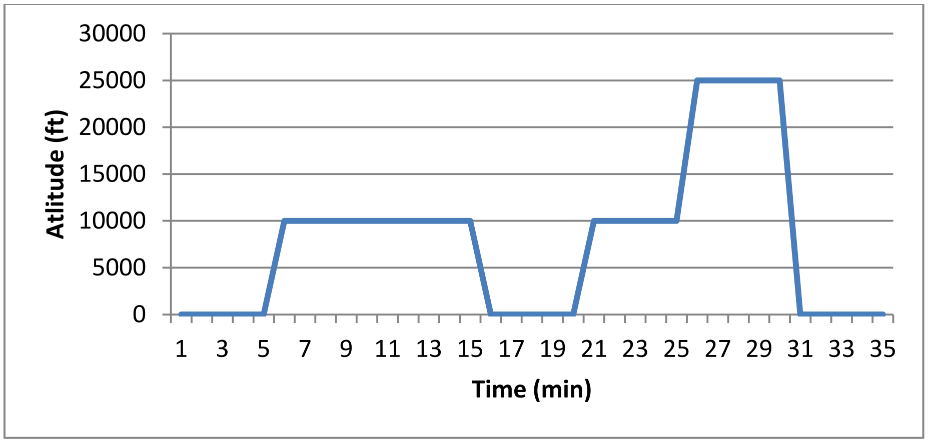

Figure 1: Familiarization session simulated altitude profile

Data Collection Session Procedures: Data collection occurred on a separate day from the familiarization session. Procedures for the data collection session were the same as for the familiarization session; however, data was collected, and a different simulated altitude profile was performed. The simulated altitude profile involved exposures of 0k, 10,000 feet (3,048 m) above MSL (10k), 18k, and 25k. The simulated altitude profile is illustrated in Figure 2. Please note that data collected during the 10k exposure were not included in the analyses nor reported in the results because exposure to 10k does not result in moderate or severe hypoxia. This altitude was only used to transition subjects to and from higher altitudes.

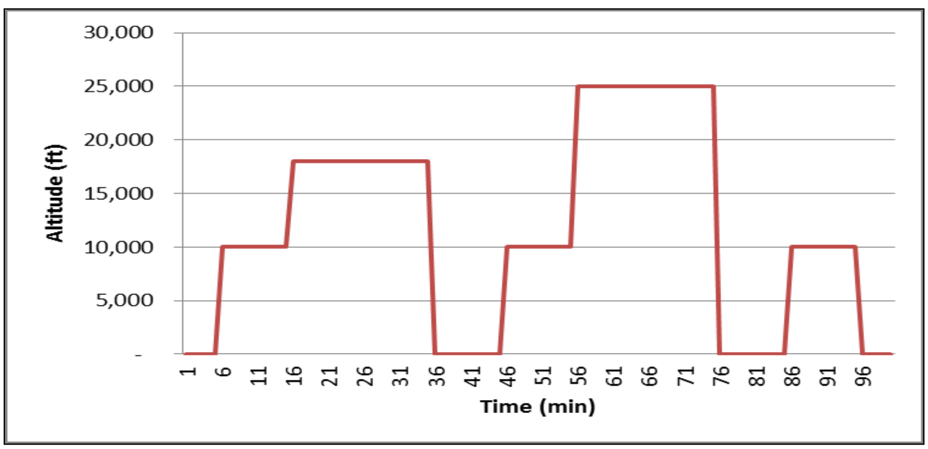

Figure 2. Data collection session simulated altitude profile

RESULTS

Descriptive statistics for both groups are presented in Table 4. The following descriptive information is for the diver group only. All subjects (N=15) began the 0k and 18k exposures with 0 and 5 aborts, respectively. Ten subjects began the 25k exposure with 9 aborts. Data for one subject who completed the 25k exposure was not included in the analyses due to a disqualifying medical condition.

The following descriptive information is for the non-diver group only. All subjects completed multiple sessions for each exposure. For the 0k exposure, there were 44 sessions in total with 11 aborts. For the 25k exposure, there were 44 sessions in total and 44 aborts.

The results of the series of two-way multivariate ANOVAs indicated that USN diver training had no effect on Fg-SpO2, PR, TUC, or SCS for the 0k, 18k, or 25k exposures.

Table 4. Descriptive statistics.

Variable		Simulated altitude		
		0k	**18k**	**25k**
Exposure length		300	1200	1200
Diver (N=15)	**Fg-SpO2 (%)**	96.40 (4.14)	78.30 (5.28)	77.26 (5.40)
	HR (bpm)	71.02 (9.96)	86.38 (11.11)	90.58 (8.85)
	TUC (s)	n/a	1025.71 (320.33)	260.67 (145.04)
	SCS	744.57 (200.05)	2396.00 (1217.74)	328.22 (446.72)
Non-diver (N=32)	**Fg-SpO2 (%)**	95.16 (7.52)	76.82 (5.36)	74.32 (3.48)
	HR (bpm)	77.35 (16.05)	91.35 (12.80)	98.49 (13.60)
	TUC (s)	n/a	1074.40 (260.10)	292.8 (181.56)
	SCS	646.08 (154.21)	2912.15 (1121.38)	577.20 (374.88)

Note. Values are means with standard deviation in parentheses. 0k = 0 feet above mean sea level; 18k = 18,000 feet above MSL; 25k = 25,00 feet above MSL; Fg-SpO2 = finger arterial oxygen saturation; % = percent; HR = heart rate; bpm = beats per minute; TUC = time of useful consciousness; s = seconds; SCS = SynWin composite score.

DISCUSSION

This study examined the effect of USN Diver training on TUC, physiological parameter measurements and cognition during periods of normobaric hypoxia. The primary findings from this study were that there were no significant differences between diver and non-diver TUC, physiological parameter measurements (i.e., HR and Fg-SpO_2 levels), and cognitive performance during any of the normobaric hypoxic exposures.

These results indicate that the initial NAWCAD subject who received USN Diver training was an anomaly.

Even without group differences there were trends in the data that can be used to further define a TUC endpoint for military personnel. All subjects, both diver and non-diver, experienced decreases in Fg-SpO_2 levels and TUC that were accompanied by increases in HR during both normobaric hypoxia exposures (i.e., 18k and 25k) when compared to the MSL exposure. These results are consistent with the published literature as hypoxia is thought to be a direct result of compromised oxygen delivery to the brain tissue due to decreased arterial pressure and arterial oxygen saturation.[18,19] The observed decreases of 19% and 20% in Fg-SpO_2 levels, for 18k and 25k, respectively, may be interpreted as decreases in arterial oxygen saturation as pulse oximetry is commonly used to estimate arterial oxygen saturation. It should be noted that Fg-SpO_2 levels in both groups were the lowest during the simulated 25k exposure, the more severe of the two normobaric hypoxia exposures.

Per the study design, TUC was partly a function of Fg-SpO_2 levels and defined as either the point where levels dropped below 60% or the point at which the subject called for 100% O_2. The TUC values during the 25k exposure will be used for comparative purposes as the published literature consistently uses 25k as a threshold for TUC. There were no significant differences for TUC between the diver and non-diver groups during the 25k exposure. TUC values were 261 ± 145 and 293 ± 182 for the diver and non-diver group, respectively. These values are similar to those found in the published literature for research performed in a low pressure chamber.[6,7,9,10] The reported TUC values were also similar to the TUC (249 ± 43 s) reported by another study performed under normobaric conditions.[4] However, it should be noted that the aforementioned study used a custom gas mixture of O_2 (6-7%) and N (93-94%) to simulate 25k rather than a ROBD.

The same study reported a mean 28% increase in HR when compared to a MSL baseline, which mirror the increases in HR seen in this study. The more severe normobaric hypoxia exposure (i.e., 25k) resulted in a higher increase in HR (22%) when compared to the more moderate normobaric hypoxia exposure (18k; 17%). These increases in HR are similar to those seen during acute exposure to hypobaric hypoxia which has been suggested to be result of a shift towards relatively more cardiac sympathetic and less parasympathetic activity especially under more severe hypoxic conditions.

Even though no direct comparisons could be made due to different exposure lengths, it appears that all subjects, both the diver and non-diver, experienced a mean 34% decrease in cognitive performance during the more severe normobaric hypoxic exposure (i.e., 25k) when compared to MSL. These results are consistent with a growing body of literature that has shown that cognitive functioning is impaired under hypoxic exposures that worsens as altitude increases and the severity of hypoxia increases.[12-14,20-23]

There were limitations in this study that may have affected the results. Data collected for each group were collected at separate sites by different research teams, and different ROBDs were used during the data collections. The non-diver group consisted of active duty, civilian, and contractor personnel, while the diver group consisted of active duty only. This difference may have affected the cardiovascular response of the subjects. Finally, no direct comparisons could be made between the simulated altitude exposures due to differences in exposures lengths, especially between the normobaric hypoxia exposures.

CONCLUSIONS

This study examined the effect of USN diver training on TUC, physiological parameter measurements, and cognition during periods of normobaric hypoxia. Even though there were no significant differences between diver and non-diver TUC, physiological parameter measurements, and cognitive performance during any of the normobaric hypoxic exposures, the results of this study can be used to further define a TUC endpoint for military personnel by providing additional data to validate the use of a 60% SpO_2 level as one input for a physiological based definition of TUC. Future research should focus on developing a model that incorporates changes in HR and blood pressure data based on the subject's individualized normative data into this physiological based definition.

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